

# **PROGRESSIVE BURN PATTERN DEVELOPMENT IN POST-FLASHOVER FIRES**

Steven W. Carman, IAAI-CFI, ATF-CFI (Retired)  
Carman & Associates Fire Investigations, Dunsmuir, CA

## **ABSTRACT**

In 2005, fire investigators from the U.S. Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) designed and presented a seminar on fire dynamics. Two identical, one-room burn cells with standard-sized doorways were each burned for seven minutes. Later, fifty-three experienced fire investigators from the public and private sectors (who had not observed the fires) were asked to briefly examine the cells and identify in which quadrant they thought each fire had started. 5.7% of the students correctly selected the quadrant of origin in each cell.

A subsequent review of experienced investigators' responses to similar, post-flashover exercises at the Federal Law Enforcement Training Center in Georgia revealed that since the early-1990s, about 8-10% of students correctly located the origins of similar fires. Those who were mistaken typically reported they were misled by burn patterns generated in fully involved, ventilation-controlled conditions.

In 2008, three follow-up tests fires were designed and conducted in single-room cells (similar to those from 2005) at the ATF Fire Research Laboratory in Ammendale, Maryland. The tests were used to evaluate burn pattern development in fully involved, ventilation-controlled fires with similar physical layouts, furnishings and ignition scenarios. The principle variable between the tests was time of exposure to full fire involvement. Analyses of heat flux, temperature and gas concentration data as well as examination of burn patterns were conducted to better understand the various mechanisms involved. Information from the tests was also used as the basis of a new Internet-based training module on Post-Flashover Fires at the training site, *CFITrainer.net*.

## **BACKGROUND**

Since the early 1990s, a major shift has occurred in the field of fire investigation. Today there is a greater emphasis on fire science and engineering than ever before. For many years, the adage that fire investigation is a mixture of "art and science" was prevalent amongst investigators who tended to focus far more on the "art" of determining where and how a fire started than on the science. While honing the "art" of fire investigation is still a part of many training programs, a focus on fire science training is more prominent than ever before. Fire investigation seminars that once shrank from technical presentations now incorporate such discussions on a regular basis. Legal precedence and the prevalence of treatises such as NFPA 921 have mandated a shift in the investigative process more towards reproducible science. Live fire testing and demonstrations coupled with science-based classes are commonplace.

In October 2005, a fire investigation seminar on fire dynamics presented by ATF Certified Fire Investigators (CFIs) and an ATF Fire Protection Engineer (FPE) coupled actual burn scenarios with classroom training. Two nearly identical, single-room burn-cells that measured 12 feet wide, 14 feet long and 8 feet high were furnished with identical contents and burned. Each had a single open doorway. Thermocouple trees were used to record gas temperatures. The cubicles were burned outside the presence of the students using similar ignition scenarios in different areas. Each exercise was designed to illustrate the importance and role of ventilation in fully involved fires. At the start of the training, a mixture of students/investigators from the public and private sectors were asked to briefly examine the scenes and to identify the quadrants of the cells in which they thought the fires started. Only 3 of 53 correctly identified the quadrants in each cell, a success rate of 5.7%.

Since around 1992 similar burns were examined at each two-week long Advanced Origin and Cause course offered by ATF at the Federal Law Enforcement Training Center (FLETC) in Glynco, Georgia. The course is used to train experienced public-sector fire investigators in advanced principles of fire science and fire investigation. At the start of each new class, students conduct a cursory examination of a “complex fire scene” and are tasked with identifying the area of fire origin and explaining their rationale. As with the 2005 burn cell exercise, the FLETC scenes are designed to gauge students’ familiarity with various concepts including ventilation-controlled burning. While written records of students’ responses were not kept, anecdotal evidence revealed that since the inception of the program, the percentage of students correctly identifying the area of origin has consistently been less than 10% of each class. Severe fire damage that occurred well after ignition and in a completely different part of the building was often misinterpreted as the area of fire origin.

### **TRAINING RESOURCES FOR POST-FLASHOVER FIRE BEHAVIOR**

The percentages of investigators correctly interpreting post-flashover burn patterns have been lower than desired. This may be in part due to a lack of focus on post-flashover fire behavior in investigator training. Fire science training for investigators is generally directed at pre-flashover fire behavior and the damage created under such conditions. Notably lacking are comprehensive discussions of both fuel- and ventilation-controlled burning. The relationship of these modes of burning are briefly discussed in popular investigation-related resources such as *NFPA 921, A Guide to Fire and Explosion Investigation*<sup>1</sup>, *Kirk’s Fire Investigation*<sup>2</sup>, and the *User’s Manual for NFPA 921*<sup>3</sup>. Unfortunately, the discussions do not always correlate burn modes with burn pattern development. There remains a need for more extensive coverage of these topics beginning in basic investigation classes.

Most training relating to fire origin determination focuses on identification and interpretation of burn patterns. Many instructors tend to explain the damage in terms of the location of burning fuel items. Plume-related burn patterns such as “V-patterns” by definition, correspond to the locations of burning fuels. This information is valid up to a transition through flashover. Post-flashover fire behavior however can vary greatly from pre-flashover situations. Techniques and theory taught for investigating pre-flashover fires must be supplemented with other information for successful post-flashover scene investigations. Too often, trainers have merely suggested that after the onset of flashover, temperatures and heat-fluxes throughout a fully involved compartment are near uniform. The 2005 fires illustrated the dangers of such thinking. In 2008, a series of test fires designed and conducted by the author, other ATF CFIs and the staff at the ATF Fire Research Laboratory (ATF FRL) was designed to gather additional information necessary to better understand the creation of burn patterns under post-flashover fire conditions. The results of the tests revealed enlightening information furthering the knowledge of ventilation-controlled burning and its impact on fire investigation.

### **POST 2005 INVESTIGATIVE / TRAINING EFFORTS**

After the 2005 demonstration burns, it became clear that a new approach was needed to improve investigators’ understanding of ventilation-controlled fire behavior. To that end, in early 2006, the author employed computational fluid dynamics modeling to compute and display visualizations of the 2005 burn cell fires. Aware of the limitations of using any computer model to simulate actual fire growth<sup>4</sup>, it was decided to make a “best effort” attempt at specifying the type and locations of the fuels and ventilation sources and run the models. If the overall results seemed reasonable, then CFD capabilities might at least prove useful for demonstrating ventilation-controlled behavior during post-flashover fire conditions. Smokeview was used to generate “snapshots” and video sequences showing calculated gas concentrations and heat fluxes at various stages. These “snapshots” were later used in presentations to explain post-flashover fire behavior. Details of the modeling efforts were set forth in an earlier review of the results<sup>5</sup>.

In each of the 2005 demonstration fires, similar wide-based areas of clean burn were generated in each

cell on the rear wall opposite the doorway. Neither of the fires was ignited in the areas of clean burn. In the first burn cell, the fire was ignited alongside the bed near the rear corner. In the second burn cell, the fire originated along the front side of the bed, about three feet from the open doorway. After the first fire, a second clean-burn pattern was also visible. It was on the wall between the bed and the chair and was attributed to fire impingement shortly after ignition. No distinct fire origin patterns survived the second fire that would have enabled any of the ATF CFIs or FPE to identify the origin despite knowing its location.

FDS modeling of the 2005 fires suggested that the most energetic post-flashover burning and accompanying high heat fluxes occurred along the pathway that oxygen-rich air flowed from the open doorway to the wall directly across the cell. Because of compartment geometry, virtually no fresh air flowed towards the first fire's origin in the rear corner behind the bed. Without an oxygen supply in that area, vigorous post-flashover burning never occurred there, leaving the pre-flashover burn patterns visible. In the second cell, because there was a plentiful oxygen supply near the fire's origin, the resulting, energetic, post-flashover burning masked the initial patterns.

Information learned from these efforts was first presented in 2006 at ATF Certified Fire Investigator training classes and later, at various training conferences of the International Association of Arson Investigators (IAAI). At each seminar, many of the principles underlying post-flashover burning were visually demonstrated using FDS data and Smokeview. During the training, the relevance of ventilation-controlled vs. fuel-controlled fires was stressed along with the principle of non-homogenous burning in post-flashover compartment fires. Investigative techniques were offered for hypothesis testing varying from simple visualization of gas flow during a fire to CFD modeling for more complex scenarios. Further, the applicability and limitations of methods such as depth of char and depth of calcination analyses were examined.

Another topic emphasized in the training was the survivability of initial fire patterns through the post-flashover period. Heat fluxes in fully involved fires were compared with those of pre-flashover conditions. Simple techniques to calculate the cumulative thermal exposure from such fluxes were provided. Throughout the training sessions it was stressed that the highest post-flashover fluxes are related to the location of ventilation sources and that the resulting fire damage is directly proportional to the time of heat exposure.

While these training sessions were welcomed by investigators and seemed helpful, it was clear that additional efforts were needed to make information quickly available to a larger audience. In early 2008, training specialists from the IAAI recommended similar training be offered through the free, internet-based training venue, *CFITrainer.net*. Subsequently, the staff of the ATF Fire Research Laboratory (ATF FRL) agreed to assist with the design and execution of follow-up burn tests to the 2005 fires, and to allow video production crews to film the tests.

Engineers at the FRL assisted in designing and three test burns that were held in July 2008 and intended to resemble the 2005 fires. New furnishings were purchased to match the previous layout as closely as possible. Cell measurements were 14 feet by 12 feet by 8 feet high. Each cell had an open doorway in the east wall with a hinged, inward swinging, hollow core door. Every cell was furnished with a dressed queen-sized mattress and box springs, two foam pads under the sheets, two pillows, wooden headboard, footboard and bed frame, an upholstered wing back chair, wooden chest of drawers, wooden dresser with attached mirror, wooden nightstand, lamp, and small plastic trashcan with 10 sheets of crumpled newsprint. Cells were also carpeted with wall-to-wall carpeting over carpet pad. Electricity was supplied and lights illuminated. The principle changes from the 2005 were one upholstered chair in place of the wicker chairs, a chest of drawers in place of a second nightstand, and no table/TV combination in the

northwest corner. An increase in fuel load of the chair was needed since the mattresses did not have high enough heat release (due to new flammability standards) to drive the cells to flashover.

More instrumentation was used in the FRL cells than in 2005 when only 2 thermocouple trees were employed. Included were four thermocouple trees, three total heat flux (THF) gauges and one radiant heat flux (RHF) gauge, four gas sensors measuring oxygen, carbon dioxide and carbon monoxide, two interior and two exterior video cameras, smoke and carbon monoxide detectors and gas velocity probes at the doorway. Numerous photos were also taken both pre- and post-fire to document the scenes. Calorimetry data was not monitored during the tests.

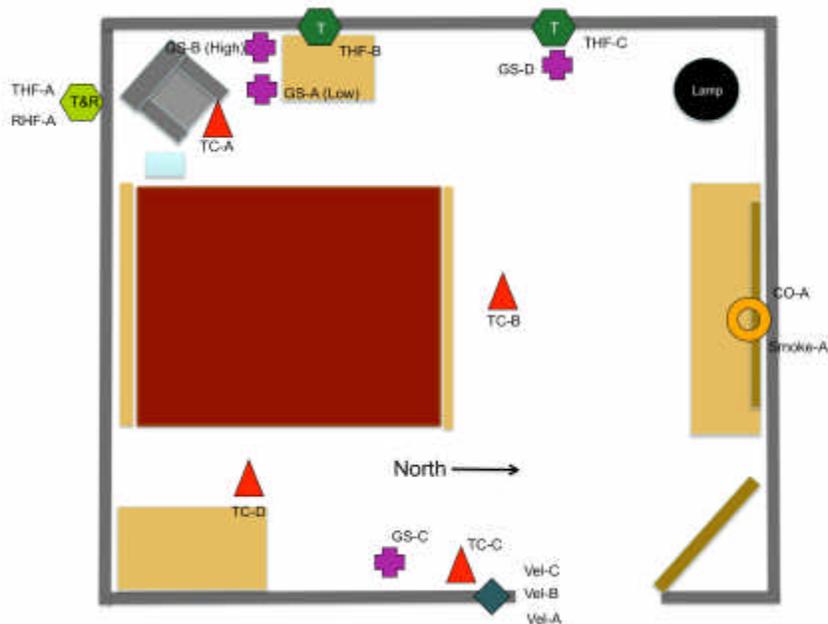


Figure 1. Layout of ATF FRL burn cells showing instrumentation

In addition to the data gathered by ATF, the production team contracted with the IAAI to design the *CFITrainer.net* module, “Post-flashover Fires” also recorded high-definition video footage during the test series. That video was edited and used in the production of the training program. A final version of the training module was released in the fall of 2008 as is available for training at <http://www.CFITrainer.net>.

The test plan called for each fire to transition through flashover. The only planned variable in each test would be the length of time the cell was allowed to burn fully involved. Ignitions would be similar to the first test in 2005 using an open flame from a butane lighter to light newspaper in a trashcan between the bed and wingback chair. Accurate determination of the onset of flashover can be challenging as several methods to identify it exist<sup>6, 7</sup>. For the FRL tests, when upper layer temperatures reached 600 °C, flashover was said to occur even though other factors commonly associated with flashover may not yet have been reached. To ensure equal datum points for measuring specific times of ventilation-controlled burning, the times of steady flame extension out of the doorways were used as reference points. The first fire was to be extinguished ten seconds after the onset of steady flame extension, and the second and third cells after two and four minutes respectively.

### ATF FRL FIRE TEST RESULTS

The complete test results for all three tests were compiled and reported by Jason Ouellette of the ATF Fire Research Laboratory staff<sup>8,9,10</sup>. The following is a summary of the three tests.

## Test Fire 1

The first burn test occurred much as anticipated. The fire was ignited in newspaper near the top of the wastebasket and at about 28 seconds, flames first reached the south wall next to the head of the bed. At 89 seconds the descending smoke layer obscured the light from the lamp in the northwest corner. At around 99 seconds, the top of the upholstered chair ignited. Upper layer temperatures at the south side of the room (TC trees "A" and "D") reached 600 °C at 137 to 139 seconds. At the time, the upper layer temperatures near the foot of the bed at TC tree "B" and inside the doorway at TC tree "C" were still around 400 °C but rose to 600 °C within about 7 seconds. It was concluded that flashover (as defined by an upper layer temperature of 600°C) occurred at about 140 seconds. Maximum temperatures in the compartment ranged between 1,000 °C at 157 seconds near the area of origin at TC tree "A" to 817 °C just inside the doorway at TC tree "C" at 210 seconds. Total heat flux readings at gauges "A" and "B" peaked at about 140 and 170 seconds respectively near 200 kW/m<sup>2</sup>. The THF readings at gauge "C" never reached much above 75 kW/m<sup>2</sup>.

Video taken inside the compartment of the west side of the bed showed steady flames at the bottom of the smoke layer between the nightstand and end of the bed at about the same time upper layer temperatures reached 600 °C. The first visible flames outside the doorway appeared about 30 seconds later at 173 seconds. A rapid drop in oxygen concentrations at gas sensor "A" from near ambient to about 4% was complete at 180 seconds. Steady flames out the door commenced at about 205 seconds, approximately one minute after flashover temperatures were reached. Average upper layer temperatures at 205 seconds were about 800°C. Extinguishment began at 212 seconds, after about 10 seconds of fully involved fire conditions.

## Test Fire 2

The plan for the second fire was to burn fully involved for two minutes prior to extinguishment. Ignition occurred as in Test 1. Unlike the vertical flame growth in cell 1, flames tended to spread laterally on the bedding. Flames did not impact the wall near the headboard of the bed until 74 seconds, approximately 46 seconds later than in the first test. Ignition of the top of the upholstered chair did not occur until 220 seconds, two minutes later than in cell 1. The top of the chair in cell 2 ignited only after the hot gas layer pyrolyzed its upper portion. Smoke layer temperatures reached 600 °C between 213 and 226 seconds and rose to a maximum temperature of around 1,000°C at TC tree "A", similar to that experienced in test 1.

Along with the difference in the time of ignition of the chair, another unexpected event occurred in test 2 when the cell door shut by itself on three occasions. It closed at 234 seconds for 9 seconds, at 256 seconds for 3 seconds and at 267 seconds for 3 more seconds. The total time of closure was approximately 15 seconds before it was wedged open by a concrete block. The oxygen concentration at gas sensor "D" dropped to below 2% when the door shut the first time. It then spiked 3% to 8% upward each time the door closed and reopened. Video of the west side of the room showed clear disruptions in air flow each time the door closed as well as substantial turbulence created at each reopening.

The first flame extension out the door was at 287 seconds and steady flame extension quickly followed at 289 seconds, about one minute after 600 °C temperatures were reached. This is comparable with the one-minute delay between flashover and steady flame extension in cell 1. At the time of steady flame extension, average upper layer temperatures were around 750 °C. Maximum heat flux readings at THF gauge "C" occurred at about 340 seconds, well after full fire involvement. Extinguishment commenced at 424 seconds, after about 140 seconds of fully involved burning. During extinguishment, a hose stream penetrated the rear wall opposite the door and caused a sheet of gypsum board to fall from the ceiling. Neither area experienced damage before extinguishment affecting the fire behavior.

### **Test Fire 3**

The test plan initially called for test 3 to burn for four minutes after steady flame extension out the doorway. After the unexpected events in test 2, it was decided that rather than allow cell 3 to burn for four minutes, the two-minute test should be repeated. Prior to commencing the test, screws were driven into the floor blocking the door open.

The fire was ignited in the same manner as the first two tests. Flames reached the wall next to the headboard of the bed at 60 seconds, 14 seconds quicker than in test 2 but at about double the time of test 1. The smoke layer descended at about the same rate as in test 1, blocking out all light from the corner lamp at around 90 seconds. Flame spread from the origin up the chair ignited the upper back at 109 seconds, 10 seconds slower than in test 1.

Upper layer gas temperatures reached 600 °C between 155 and 162 seconds, approximately 20 seconds later than in test 1, but a minute earlier than in test 2. The maximum temperature of around 1,100 °C occurred at TC tree "A" at 175 seconds and then dropped. Initial, temporary flame extension through the door was seen at 161 seconds and steady flame extension occurred at 246 seconds. The delay between 600 °C upper layer temperatures and steady flame extension in test 3 was about 90 seconds, compared to a one-minute delay in each of the other tests. By the time of steady flame extension, the average upper layer temperature was about 750 °C.

Two peak total heat flux readings occurred in test 3 at THF gauge "C". The first peak of about 215 kW/m<sup>2</sup> was at 270 seconds, 24 seconds after steady flame extension. Fluxes at "C" then dropped to about 80 kW/m<sup>2</sup> before again rising to over 220 kW/m<sup>2</sup> at about 345 seconds. THF gauge "A" peaked at about 215 kW/m<sup>2</sup> at 154 seconds about the time upper smoke layer reached flashover temperatures. Shortly thereafter, THF gauge "A" stopped working.

Oxygen concentrations at gas sensor "D" fell to a low near 0% at about 212 seconds after ignition. For an unknown reason, the oxygen values at the same sensor then rose for 20 seconds to a peak of around 13% before again dropping to around 3%. It then dropped more slowly rate to less than 1%. Extinguishment commenced at 357 seconds enabling test 3 to burn fully involved for about 111 seconds.

### **FIRE TEST SCENE EXAMINATIONS**

A major objective of the test series was to examine burn pattern creation under differing times of fully involved burning. Because of the unexpected airflow disruptions in test 2, it was initially expected that the patterns in that test might not provide useful data. Accordingly cells 1 and 3 were first examined to identify burn pattern variations due to different burn times.

#### **Cell 1**

In cell 1, burn patterns alone indicated the room had been close to flashover. Because the bottom of some furnishings had not burned, without witness statements indicating steady flame extension, an investigator may have concluded flashover had not occurred. An area of fire origin was identified near the trashcan between the bed and upholstered chair. A "V-pattern" was obvious amidst the vertical slats of the headboard showing flames or hot gases rising up from between the bed and the chair. Also, an off-white 'clean burn' pattern was clearly visible on the south wall where flames initially contacted it. The irregular pattern measured about 18 inches across and was located between the top of the headboard and the top of the wingback chair. It was similar to the plume pattern in the first 2005 test fire created by the originating fire.



Figure 2. View to S in cell 1 showing clean burn on wall near origin



Figure 3. View to SE in cell 1. Localized damage to mattress and frame is evident



Figure 4. View to W in cell 1 showing areas of clean-burn on south and west walls



Figure 5. View to NW corner of cell 1. Note lesser damage towards the north end

Clear delineation of burn damage to the mattress fabric was visible suggesting a heat source between the bed and chair. A plume-impact, clean-burn pattern was on the ceiling generally above the trashcan and chair. Uneven burn damage to the right arm of the chair revealed more fire damage on the outside of the chair closest to the bed than elsewhere. Protected areas on the gypsum wallboard were visible behind the chair and nearer to the nightstand.

At the north end of the west wall, almost no damage had occurred to the wallboard near floor level. On the wall above the nightstand was what appeared to be the start of an area of clean burn. Elsewhere on the wall, smoke staining was worse towards the south end of the room.

### Cell 3

Post-fire examination revealed clear evidence of fully involved, post-flashover fire conditions. The walls were badly smoke stained to floor level. Two glaring burn patterns were immediately obvious upon entering the compartment. First, a large “V-pattern” of clean burn was visible on the west wall and centered just north of the nightstand. The apex of the pattern was about 15 inches above the floor. The lower portion of the “V” had nearly vertical sides about a foot high above which the sides of the “V” spread outward. On the ceiling above the “V” was a wide area of extensive damage where the wallboard had badly cracked and nearly failed.



Figure 6. View to W wall of cell 3 showing a large, clean-burn “V-pattern”



Figure 7. View of N wall of cell 3 through the doorway. Note the area of clean-burn.

The second area of extensive clean-burn was located on the north wall between the dresser and the open door. It extended from floor level up about three feet (to near the top of the dresser) and formed a pattern similar to an “inverted-V”. The end of the dresser next to the pattern, though charred was intact. The frame of the door east of the pattern was also badly charred but intact. The center web or panel of the door had burned away. The wall above the clean burn was smoke stained and less badly damaged than the area below it. The ceiling directly above the clean burned area showed no indications of circular patterns as might be expected from plume impact.

The fire did not cause an area of clean burn on the south wall near the origin as had occurred in cell 1. Since the fires were started in the same manner, participants expected to find a similar clean-burn from early flame contact. The wooden slats making up the headboard had, as in cell 1, burned in a “V” which appeared to be caused by flames or hot gases spreading out from between the bed and the chair. Damage to the wooden frame of the upholstered chair was slightly greater on the east side. Similarly, damage to the bed frame was most extensive near the area of origin. Without more information, the bed and chair burn patterns could have been attributed to the close proximity of burning fuels.

Damage to the mattress was uneven. Next to the area of origin, the fabric had mostly burned away. Similar damage occurred on the east side of the mattress close to the open doorway. The damage near the doorway was more extensive than that nearer the origin.



Figure 8. View to SW in cell 3 showing damage to the bed’s east side near the door



Figure 9. View to SE in cell 3. Note the absence of clean-burn near the origin

## Cell 2

Because of the irregularities experienced in test fire 2, participants examined cell 2 last. Upon entry, a large clean-burn “V-pattern” was clearly visible on the west wall. The pattern was very similar in shape and location to a corresponding pattern in cell 3. The apex of the “V” in cell 2 was about 14 inches above the floor and north of the nightstand with almost the same location, shape and size as the pattern in cell 3. As in cell 3, the bottom section of the clean-burn had near vertical sides that further up, spread outward.



Figure 10. View to W in cell 2 showing the clean-burn “V” similar to cell 3



Figure 11. View to N in cell 2. Note the lack of clean burn to the right of the dresser

No remarkable fire patterns were visible on the north or east walls of the cell. The doorframe of cell 2 had mostly burned away unlike in cell 3. No area of clean burn was visible between the edge of the door and the dresser. The concrete block used to prop the door open during the test likely protected the area behind it from extensive burning.

As in cell 3, there was no clearly visible, clean-burn pattern in cell 2 on the south wall near the fire origin. Close examination of the area revealed light cracks in the surface of the wallboard where flames contacted the wall, however no obvious surface discoloration was visible. Consistent with cells 1 and 3, the headboard in cell 2 showed indications of a “V-pattern” extending upwards from between the bed and the chair. Visible damage to the wall between the mattress and the chair was generally unremarkable.



Figure 12. View to S in cell 2. Note the lack of clean burn near the origin



Figure 13. View to SE in cell 2. Note more severe mattress damage than in tests 1 & 3

The bed frame next to the origin was the most badly damaged section. As with cell 3, the damage could, without additional information, be attributed to the upholstered chair burning mere inches away. Overall, mattress damage was the greatest in test 2, probably because the second fire burned longer than had the others.

### **Additional Observations**

The “V-patterns” on the west walls of cells 2 and 3 were remarkably similar yet clearly bore no relationship to either of the fires’ origins which were approximately six feet from the apex of each “V”. No fuels other than carpeting had been below the patterns prior to the fire. The west wall of cell 1 showed an area of clean-burned, wallboard damage in the same general location as the upper left portions of the clean-burned “V”s in cells 2 and 3. Had test 1 been allowed to burn longer, it is likely that the existing small area of clean burn would have grown to become more like those areas in the other cells.

The west wall “V-patterns” in tests 2 and 3 were located in the same general areas as the worst damage in the test fires from 2005. In those fires, the more extensive damage was theorized to be due to increased heat fluxes on the rear walls caused by the inflow of fresh air during ventilation-controlled burning. FDS calculations also showed that incoming air could have led to the higher heat fluxes on the west wall. While not measured in the 2005 tests, calculated heat fluxes were in the range of 150 kW/m<sup>2</sup>.

While the cells and furnishings layouts in the FRL test fires were similar to the 2005 tests, there were some differences. First, there was no table in the northwest corner of the FRL cells. Additionally, the bed frames used in 2005 did not elevate the box springs off of the floor as occurred in the FRL tests. The bottoms of the beds at the FRL were approximately eight inches above the carpet, allowing for free flow of gases under the beds once the lower portions of the bedspreads burned away. This air movement under the bed was clearly visible in the interior video. Such low level, below-bed airflow did not occur in 2005 since the box springs were placed on the floor.

THF gauge “C” measured a significant rise in total heat flux in tests 2 and 3 only after the onset of ventilation-controlled burning. Heat fluxes at gauge “C” never did rise appreciably in test 1, likely because the fire was extinguished shortly after full involvement. As in the 2005 fires, heat fluxes along the west walls of the FRL cells were higher after the fires became ventilation-controlled. This is because inflowing fresh air enabled efficient combustion of the unburned fuel gases along the airflow path unlike in other areas of the room where available oxygen could not reach. Clearly, investigators much consider these ventilation-related behaviors when examining burn patterns in post-flashover fires.

The clean burn in test 3 between the door and the dresser is due to the efficient mixing of unburned fuel gases and swirling air currents from incoming airflow. In the test video, swirling eddies of low level, incoming air are clearly visible at the north side of the doorway. This turbulent flow enabled efficient mixing of available oxygen with fuel gases in the area. The reason such damage did not occur in test 2 is probably because the concrete block at the base of the door interrupted the eddy formation. Had the clean-burn damage along the dresser in cell 3 been caused by a fire origin, one would have expected to see plume-related patterns at the upper reaches of the wall above the pattern and on the ceiling where plume would have impacted.

In the first of the 2005 test fires, an area of clean burn was clearly visible on the wall near the fire’s origin. Only in the first of the three FRL test fires did a similar pattern occur. The question arises as to why no such patterns were seen after test fires 2 and 3 since all of the fires were ignited the same way. Did a similar pattern exist early on in those fires but was later covered up or masked? If so, what was responsible for the disappearance? Video clearly shows flames from the origins impacting the south wall in all three fires. One untested theory explaining the “missing” patterns in the final two tests is that after the fires became ventilation-controlled, an excess of fuel gases in the vicinity of the wingback chair, (a type not used in the 2005 fires) remained unburned because of insufficient oxygen in the area to support combustion. The unburned pyrolyzates then condensed on the wall surface covering or masking what may have been initial areas of clean-burn. Subsequently, no localized burning existed in that area that might have burned away the condensate.

To ascertain if depth of calcination data might assist in post-flashover scenes to determine areas of origin, measurements were made in each of the three cells. A depth gauge commonly used to measure depth of calcination damage was employed along the rear wall and in the areas where initial clean burn either existed or was expected but not found. The measurements offered no particular insight other than to show that even though no clean-burn was visible in tests 2 and 3 near the initial area of fire impact, localized areas of more extensive calcination were present. Whether such data could be successfully used to test origin hypotheses is uncertain. Because of the nearby presence of significant amounts of polyurethane foam in the wingback chair, investigators would likely have a difficult time eliminating the heat exposure from that burning foam in contributing to such calcination.

With regards to the measurements of calcination depth in and around the larger “V-patterns” on the west walls, depths were, as expected, greater in areas with more extensive clean-burn. Not only were the measurements greater than at nearby areas outside the “V”s, they were also substantially greater than the areas on the south walls where flames from the fires’ origins first made contact.

#### **ADDITIONAL RECOMMENDED EFFORTS**

Though not yet completed, CFD analysis is in order for the three FRL test fires. Minor changes in layout and type of furnishings from 2005 may have contributed significant changes in airflow throughout the compartments. Comparisons of computed data with that obtained during the actual tests would be beneficial in judging the usefulness of CFD modeling in estimating air flow in post-flashover compartment fires.

Additional full scale testing with the addition of more or varied vents would also be insightful. To date, five similar tests have been conducted and analyzed, yet in each test, only one open door was employed, always in the same location. Multiple vents, larger or smaller vents, vents in different locations and different lengths of time the vents are open are all worthwhile variables to investigate and compare with the existing test data. Different compartment sizes and furniture arrangements would also be important variables to consider. Lastly, the effects of fully involved compartment fires venting to rooms other than the outside are of interest since the incoming air for the fire compartment would then potentially be vitiated and less capable of supporting combustion than fresh air.

#### **ACKNOWLEDGEMENTS**

The author gratefully acknowledges the fine work and assistance of all the management and staff of the ATF Fire Research Laboratory especially Jason Ouellette, Dr. David Sheppard and Director John Allen. Their efforts to advance the understanding of post-flashover fire investigation are greatly appreciated.

#### **ABOUT THE AUTHOR**

**Steven W. Carman, IAAI-CFI ATF-CFI (Ret)**, Carman & Associates Fire Investigation, Dunsmuir, CA Mr. Carman retired as an ATF Senior Special Agent in July 2008. He holds a B.S. degree with High Honors in Physical Science from the U.S. Coast Guard Academy. Mr. Carman’s previous works include, “High Temperature Accelerant Fires”, “Behavior of High Temperature Incendiaries”, and “Improving the Understanding of Post-Flashover Fire Behavior”. He has lectured internationally on various aspects of fire science and investigation including fire dynamics, fire chemistry and fire modeling.

## REFERENCES

- <sup>1</sup> NFPA 921, 2004, *Guide for Fire and Explosion Investigations*, NFPA, Quincy, Massachusetts.
- <sup>2</sup> DeHaan, J.D., 2007, *Kirk's Fire Investigation*, 6th Edition, Pearson/Prentice Hall, New Jersey.
- <sup>3</sup> *User's Manual for NFPA 921*, 2003, NFPA / IAAI, Quincy, Massachusetts.
- <sup>4</sup> Utiskul, Y., 2007, "Theoretical and Experimental Study on Fully-Developed Compartment Fires", *NIST GCR 07-097*, University of Maryland.
- <sup>5</sup> Carman, Steven, "Improving the Understanding of Post-Flashover Fire Behavior", Proceedings of the International Symposium of Fire Investigation Science & Technology, May 2008
- <sup>6</sup> Peacock, Richard D., Reneke, Paul A., Bukowski, Richard W., Babrauskas, Vytenis, "Defining Flashover for Fire Hazard Calculations", *Fire Safety Journal* 32 (1999), 331-345.
- <sup>7</sup> Babrauskas, Vytenis, Peacock, Richard D., Reneke, Paul A., "Defining Flashover for Hazard Calculations: Part II", *Fire Safety Journal* 38 (2003), 613-622.
- <sup>8</sup> Oullette, Jason, "ATF FRL Fire Test Report 3589", August 26, 2008, Ammendale, Maryland
- <sup>9</sup> Oullette, Jason, "ATF FRL Fire Test Report 3593", August 26, 2008, Ammendale, Maryland
- <sup>10</sup> Oullette, Jason, "ATF FRL Fire Test Report 3595", August 26, 2008, Ammendale, Maryland